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Determination of prestressing force in railway concrete sleepers using dynamic relaxation technique

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Abstract: Prestressed concrete sleepers (or railroad ties) are designed in order to carry and transfer the wheel loads from the rails to the track foundation. Over a period of time, a railway track could experience various types of static and dynamic loading conditions, which are attributable to commercial train operations. Previous studies have established two main limit states for the design consideration of concrete sleepers: ultimate limit states under extreme impact and fatigue limit states under repeated probabilistic impact loads. Prestressed concrete has played a significant role as to maintain the high endurance of the sleepers under low to moderate repeated impact loads. In spite of the most common use of the prestressed concrete sleepers in railway tracks, their remaining lives are not deeply appreciated nor taken into account for track maintenance and renewal. This experimental investigation was aimed at determining the residual prestressing force of railway concrete sleepers after revenue services using the dynamic relaxation technique. Fifteen sleepers were extracted from a heavy haul rail network for testing using experimental facilities at the University of Wollongong Australia. Structural evaluation program included quasi-static bending tests, dynamic impact tests, and tests to establish the current level of prestress in the steel wires using the dynamic relaxation technique. Two of the sleepers were evaluated for the level of prestressing forces in accordance with Australian Standards. It is found that the level of prestress determined using the dynamic relaxation technique turned out to be significantly lower than that expected from the theoretical analysis of time-dependent prestressing losses for the concrete sleepers.

Keywords: Prestressed concrete sleeper; Remaining prestressing force; Accumulative damage; Dynamic relaxation technique; Ballasted railway track.

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Introduction

In Australia, railway prestressed concrete sleepers have been used in a rail network for nearly 35 years in comparison with those experiencing about 50 years in European and Japanese rail networks. The railway sleepers (or called 'railroad tie' in the US) are a main part of railway track structures. Its main duty is to distribute loads from the rail foot to the underlying ballast bed. Based on the current design approach, the design life span of the concrete sleepers is also considered around 50 years (Standards Australia, 2003). Typical ballasted railway tracks and their components are shown in Figure 1. During their life cycles, railway track structures experience static, dynamic and often impact loading conditions due to wheel/rail interactions associated with the abnormalities in either a wheel or a rail (Remennikov and Kaewunruen, 2008). It was found that the magnitude of the dynamic impact loads per railseat is varying from 200 kN and sometimes can be more than 600 kN, whilst the design static wheel load per railseat for a 40-tone axle load could be only as much as 110 kN. In principle, wheel load is an important factor in design and analysis of railway track and its components. The design load (F^*) for the limit states design concept takes into account both the static (F_s) and dynamic (F_i) wheel loads. There are three main steps in designing the concrete sleepers. First, the design actions or loads are to be determined based on the importance level of the track (e.g. $F^* = 1.2\ F_s + 1.5\ F_i$). Then, the design moment can be achieved by converting the design load to sleeper bending moment envelopes using advanced railtrack dynamic analysis or the design formulation (Kewunruen and Remennikov, 2008; 2009). Last, the strength and serviceability of the prestressed concrete sleepers can be optimized in accordance with AS3600 Concrete structures (Standards Australia, 2001).

Recent studies showed that it is very likely that a railway sleeper could be subjected to severe impact loads, resulting in a rapid deterioration of its structural integrity and durability (Esveld, 2001; Kaewunruen, 2007; Leong, 2007; Kaewunruen et al., 2014). A major research effort at the University of Wollongong (UOW) has revealed that the failure of a railway sleeper is more likely due to the cumulative damage rather than due to only a once-off extreme event, which might occur due to the derailment or the terrorist attack. However, it was found that, for prestressed concrete sleepers, the low magnitude but high cycle impact fatigue tend to be insignificant in comparison with the high magnitude but low cycle impact fatigue (Ye et al., 1994; Wang, 1996; Wakui et al., 1999; Gustavson 2002; Stevens and Dux, 2004; and Kaewunruen, 2007). According to the literature review, it appears that there exists no research investigation into residual condition or remaining life prediction of concrete sleepers. These have caused either incorrect or inefficient asset management under constantly changing operations in the real world. This practical issue has resulted in an initiative to investigate the existing condition of railway concrete sleepers and to develop a standard guidance for predicting the remaining life of such component. The strength and capacity of concrete sleepers depend largely on the prestressing force and bonds between steel strands and concrete (Warner et al., 1998). Loss of prestress can generally be classified into two stages: initial loss and time-dependent loss. Initial loss of prestress in concrete sleepers (due to elastic shortening, bond and friction, and anchorage set) at the release of prestress was measured to be between 20 and 27 percent - depending on the type of strands, bond characteristics, concrete materials and the workmanship during the processes of prestress release (Kaewunruen, 2007). Over the time, the concrete sleepers experience various traffic loads and may incur any damages and cracks, resulting in a further time-dependent loss in prestress level (due to shrinkage and creep of concrete, and relaxation of steel). The phenomena also incur even without external loading. This paper addresses a part of the main initiative with respect to the determination of remaining prestressing force in concrete sleepers after a period of service life using dynamic relaxation method.

This investigation arose from planned expansion of the traffic on the heavy haul coal line in New South Wales (NSW), Australia. The company planned to double the traffic on that coal line and was concerned about the ability of its railway concrete sleepers (SRA types 1 and 2 concrete sleepers on the coal line) to carry the increased traffic loads. The sleepers on that coal line were manufactured and installed in 1982-84. A cluster of fifteen in-service concrete sleepers that were installed in a heavy haul rail network were pulled out from the rail track and shipped to the structures laboratory at UoW, Australia. Visual inspections and laboratory material testings were conducted at the initial stage of the project. Two of the sleepers were evaluated for the level of prestressing forces based on the design method in accordance with Australian Standards. This paper presents the experimental study into the remaining prestressing force of existing aged prestressed concrete sleepers. Also demonstrated are the engineering characteristics of materials used for manufacturing concrete sleepers.

Experimental Overview

Test specimens

Fifteen sleepers were retrieved from the heavy-haul coal line and delivered to UOW in July 2011 for testings in accordance with Australian Standards AS1085.14 (2003). The railway operator and maintainer confirmed that the sleepers were typical heavy-duty sleepers manufactured around 1982. Design parameters detailing concrete strength, level of prestress, design moment capacities were not available and therefore could not be used in this project for the direct comparison of the current design parameters to the original design parameters at the time of sleeper manufacture. However, it was reported from industry practices that the permissible stresses and design restrictions of the concrete sleepers back in 1980s are very similar to those in existing standards (Standards Australia, 2003). There was not much change in the standard design methodology and inputs over the past decades. The design characteristics as tabulated in Table 2 were thus adopted from AS1085.14 and AS3600, respectively (Standards Australia, 2003; 2001)

In this investigation, two test specimens are typical full-scale prestressed concrete sleepers commonly used in Australia, as shown in Figure 2. Two test specimens were selected to demonstrate the variation and importance of detecting prestressing loss in currently used aged concrete sleepers. The prestressed concrete sleepers are often the main part of the standard-gauge, heavy-haul rail tracks. The measured dimensions of the prestressed concrete sleeper are given in

Table 1. The cross-sections of the prestressed concrete sleeper were optimized for specific load carrying capacities at different functional performances for rail seat and mid span. The prestressing tendons are the chevron-patterned indented wires of about 5mm diameter (Standards Australia, 2003). The high strength concrete material was used to cast the prestressed concrete sleepers, with design compressive strength at 28 days of 50-55 MPa, and the prestressing steels used were the high strength with rupture strength of 1700 MPa (or 0.2% proof stress of 1530 MPa). The cored samples, drilled from the sleepers, were taken for a confirmation test, as per the Australian Standard AS1012.14 (Standards Australia, 1991), as shown in Figure 3. Although the common concrete strength adopted for design is 50 MPa, it was found that condition of the concrete at the test age of about 30 years (since 1982) was deteriorated. From visual inspection, it could be observed that the high strength prestressing wires were of high quality and the strength would not rapidly change during time.

Material testing

Core samples were taken from the two sleepers. The cored samples, drilled from the sleepers, were taken to confirm the material properties of the tested concrete sleepers, in accordance with the Australian Standard AS 1012.14 (1991). The standard recommends avoiding the top layer of a concrete member, as it may be of lower strength than the bulk of the concrete. There can be a strength gradient within the concrete, increasing with depth below the surface resulting from curing and consolidating effects. In their manufacture, the sleepers are cast upside down, therefore coring from the bottom was avoided.

The ends of the two sleeper specimens were cut clean from the rest of the sleeper at the location of the rail seat, as shown in Figure 4. The sleeper ends were then placed upright and the cores extracted from the freshly cut interior face. Cores were extracted from between the two rows of prestressing wires from each of the two specimens.

Once the cylindrical cores were extracted from the sleeper ends, they were checked for overall smoothness, steps, ridges and grooves. The ends of the samples were trimmed and finished to a smooth flat surface with the length-to-diameter ratio maintained at 2:1.

Dynamic relaxation technique

Experimental verification of prestressing force in the prestressing wires was conducted using a dynamic relaxation technique. Dynamic relaxation is a process whereby 100 percent relaxation of the steel wire is induced in an instant, relieving all remaining prestress (Otter et al., 1966; Saiidi et al., 1994; Nawy, 1996; Lundqvist, 2012). Using the technique of dynamic relaxation, the prestressing force in the prestressed wires was determined. With the knowledge of the final state of strain in the wires after relaxation and Hooke's law for the prestressing steel, the prestressing force was calculated for the individually tested wires. To perform the test, three specimens were prepared. Two sleepers extracted from the coal line under investigation were prepared in accordance with Australian Standards (1991, 2001, 2003) while an additional concrete sleeper (similar type) removed from another mixed-traffics railway track in NSW was used for comparison and validation of the results.

The top 30 mm of concrete cover was removed from the specimens to expose the top row of the reinforcing wires near the centre of the sleepers. The mid-span position was chosen to ensure adequate anchorage zone of prestressing tendons surrounding the test zone. A small area of concrete was removed from underneath the wires to eliminate the steel-concrete bond and ensure complete freedom of the wires for longitudinal displacement during the test as shown in Figure 5. In total, less than 5 percent of concrete was removed axially along the sleepers in order to ascertain that the concrete cover removal did not critically affect the prestress level and eccentricity according to AS3600 (Standards Australia, 2001). The wires were polished and cleaned and had strain gauges with a 2 mm gauge length attached by using dynamic strain gauge epoxy resin as shown Figure 6. The strain gauges were attached to symmetrical wires on each specimen. The strain gauges were connected to the high-speed data acquisition system. The data logger was calibrated to process and capture changes in axial strains at the rate of 10,000 data points per second, anticipating a very sudden relaxation of the wires.

After attaching the strain gauges to the wires, the strain gauged wires were cut one at a time using bolt cutters, as seen in Figure 7. The cutting process was swift and very minimal disturbance on the dynamic strains can be observed in Figure 8. Cutting the wires released the tensile stress that the wires were subjected to during prestressing. Rapid removal of this stress provoked axial vibration of the steel wire that was recorded as a time history of strains by the high-speed data logger. Note that the residual effect of strain relaxation on the condition of strain gauges is negligible as shown in the final state of strains in Figure 8. It was observed that the dynamic strains could be acquired reliably using dynamic strain gauges and there was no slip nor delamination of strain gauges after the tests.

Material Properties

Five compressive tests were conducted using compression testing apparatus in the High Bay laboratory at the University of Wollongong. The tests were performed in accordance with concrete compressive testing procedures outlined in AS 1012.9-1999 (Standards Australia, 1999). Table 3 presents the results of concrete compressive tests. The average compressive strength of the tested core samples was found to be 44.2 MPa.

The typical characteristic concrete compressive strength (after 28 days) in prestressed concrete sleepers is 50 MPa. It was expected that the 30-year old concrete sleepers would develop compressive strength around 65-80 MPa (Kaewunruen and Remennikov, 2010; 2014), thus the experimentally determined concrete strength of 44.2 MPa (± 4 MPa) was much lower than that expected. There was no known reason for such significant degradation of the concrete compression strength over the service life period, unless the sleepers were originally manufactured with very low strength of concrete of around 25-30 MPa.

Experimental results and discussion of dynamic relaxation tests

Figures 8 (a) and (b) present the time histories of axial strain from the dynamic relaxation of the wires for the two sleepers tested. The graphs demonstrate how the strain relaxed over a very short period of time before settling on a final constant value representing the actual prestressing force. Upon cutting, the sudden release of prestressing force causes the exposed portion of wire to undergo a rapid shortening along its length, expressed as a sudden drop in strain on the graphs. Due to the inertial effects, the wire segment vibrates with rapidly decreasing amplitudes due to damping and friction effects generated by the steel-concrete interface. The calculated differential strain from the initial prestressed state to the final relaxed state is approximately 2000 microstrain for both sleepers tested, as seen in Figures 8 (a) and (b).

Adopting a modulus of elasticity of 200 GPa for the steel tendons and using the experimentally determined axial strain of 2000 microstrain, the steel wire stress can be calculated as

$$\sigma_{s,1} = E_s \cdot \varepsilon_{s,1} = \left(200 \times 10^3\right)\left(MPa\right)\left(0.002\right) = 400 MPa \tag{1}$$

With the 0.2% proof stress of 1530 MPa, the theoretical design value of prestressing stress should be about 0.85 *x* 1530 = 1300 MPa. Allowing for 20% initial loss of prestress at the sleeper centre, the design stress in the steel wires should have been 1040 MPa in the top row of wires. This shows that the experimentally determined level of prestress is just about 40 percent of the expected stresses in the prestressing tendons in the coal-line sleepers tested herein.

The experimentally determined values of the prestressing force were validated by utilising the same experimental procedure to determine the level of prestress in a heavy-duty sleeper (similar type) extracted from the mixed-traffic track near Wollongong, NSW. It is estimated that the heavy-duty sleeper has been in service for about 10 years and subjected predominately to suburban train loads.

Figure 9 demonstrates the time histories for the axial strains from the dynamic relaxation of the top row wires at the centre of heavy-duty sleeper. One can notice that the average measured strain from relaxation for the two wires was approximately 5200 microstrain. Adopting a modulus of elasticity of 200 GPa for the steel and using the experimentally determined axial strain of 5200 microstrain, the steel wire stress can be calculated as

$$\sigma_{s,2} = E_s \cdot \varepsilon_{s,2} = \left(200 \times 10^3\right)(MPa)(0.0052) = 1004\,MPa \qquad (2)$$

which is reasonably close to the theoretical design stress of 1040 MPa in the top row of wires at the sleeper centre, or about 23% loss from the initial design prestress, which is justifiable. According to AS1085.14 (Standards Australia, 2003), the prestress level at transfer only (or without any applied wheel load) should remain approximately consistent. Note that the overall cross-section relationship between fibre stresses (σ), prestressing forces (P_s) and eccentricity (e) can be correlated as:

$$\sigma = -\frac{P_s}{A_g} \pm \frac{P_s \cdot e \cdot y}{I_g} \qquad (3)$$

where y is the moment-arm distance from neutral axis, A_g and I_g are the gross area and moment of inertia of cross section, respectively.

Based on the validating results for the heavy-duty sleeper, it is believed that the experimentally determined value of prestress is justified, and it indicates significant loss of prestress in some existing coal-line sleepers tested in this programme. One possible explanation of the above phenomenon is illustrated in Figure 10, showing one of the tested sleepers with a significantly damaged end. This type of concrete damage may have resulted in the loss of bond between the steel wire and the concrete and reduction in the level of prestress in the steel wire. But, the second sleeper tested did not have significant concrete damage and also showed a very low level of the prestress. It is therefore recommended that the proposed experimental technique for determining the level of prestress in the existing concrete sleepers is adopted as part of assessment of remaining life of sleepers in the existing heavy haul train lines.

Conclusions

This paper presents a part of the investigation arose from the planned expansion of the traffic on the heavy-haul coal lines by a rail operator and maintainer. There was a concern whether the railway concrete sleepers would be capable of carrying the increased traffic loads. Note that the concrete sleepers on that coal line were manufactured and installed in 1982-84.

Accordingly, fifteen aged concrete sleepers that were installed in the heavy haul rail network were extracted from the rail track and shipped to the structures laboratory at the University of Wollongong (UOW), Australia. Visual inspections and laboratory material testings were conducted. The sleepers were evaluated for their current positive and negative bending capacities, fatigue resistance, and resistance to impact loading. Several sleepers were evaluated for the current level of prestressing forces in accordance with Australian Standards.

The visual inspection of the concrete sleepers revealed that there were potential problems with durability of the sleepers. Concrete spalling of sleepers due to tamping damage, poor construction, and loss of concrete section due to abrasions were among the problems that could cause the rapid deterioration of strength and serviceability.

It is found that the dynamic relaxation technique is a suitable procedure for the determination of the level of prestress in existing aged concrete sleepers. Using this technique, it was possible to detect the existing sleepers in which the current level of prestress in the steel wires was only 40 percent of the design value. The experimental results demonstrated that loss of prestress could be linked to the integrity of the concrete material, which could be used for initial screening of the existing concrete sleepers with a view of detecting defective sleepers. This information is also critical for predicting remaining life of concrete sleepers in existing railway tracks and their ability to sustain higher wheel loads or higher train speeds when expansion of the traffic is planned.

It is important to note that loss of prestress affects serviceability (rail gauge widening, cant dynamics, rotational capacity at rail seats, dynamic geometry and deflection, etc.) and durability (i.e. fatigue life, crack propagation, etc.) of sleepers. The future investigations will include the material strengths, structural capacity, spectrum of impact loads from the wheel impact detectors, and responses of the concrete sleepers to impact and fatigue loading conditions, in order to predict their remaining capacity of concrete sleepers to cater for the current or planned increased traffic loads.

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Table 1. Dimensions and masses of the test sleepers

Mass (kg)	Gauge length (m)	Total length (m)	At railseat (m)		At centre (m)	
			width	depth	width	depth
206.0	1.60	2.50	0.20	0.23	0.21	0.18

Table 2. Design properties of materials

Materials	Elastic modulus (MPa)	Compressive strength (MPa)	Tensile strength (MPa)
Concrete	38,000	55	6.30
Prestressing tendon	200,000	-	1,700
Steel rails	205,000	-	-

Table 3. Tested compressive strength of concrete

Core No	**Mean diameter (mm)**	**Ultimate load (kN)**	**Compressive strength (MPa)**
1	54.20	114	49.4
2	54.39	100	43.1
3	54.18	90	39.1
4	54.24	102	44.1
5	54.26	105	45.4
Average			44.2

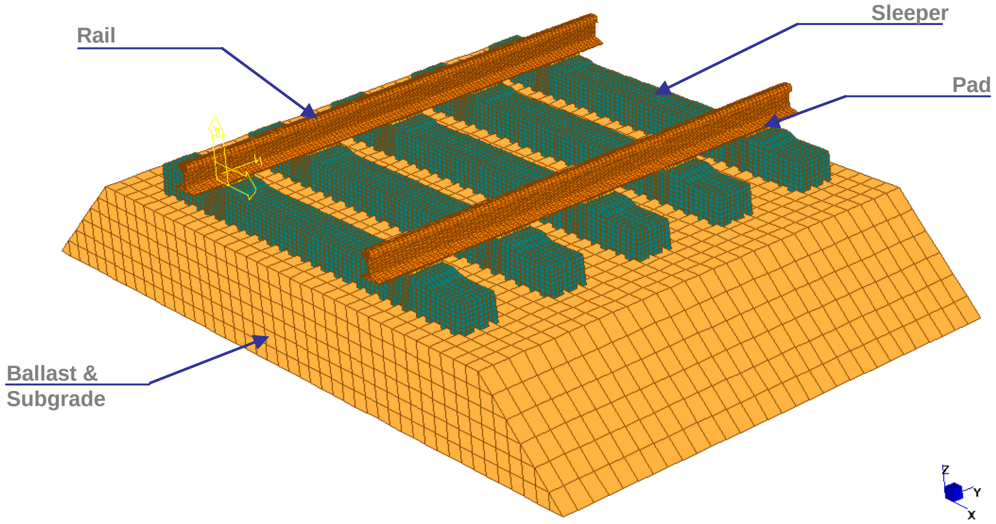


Figure 1. Typical components of railway tracks.

Figure 2. Condition of concrete sleepers

Figure 3. Preparation of concrete samples (left: coring machine; and right: cored concrete samples prior to compression testing).

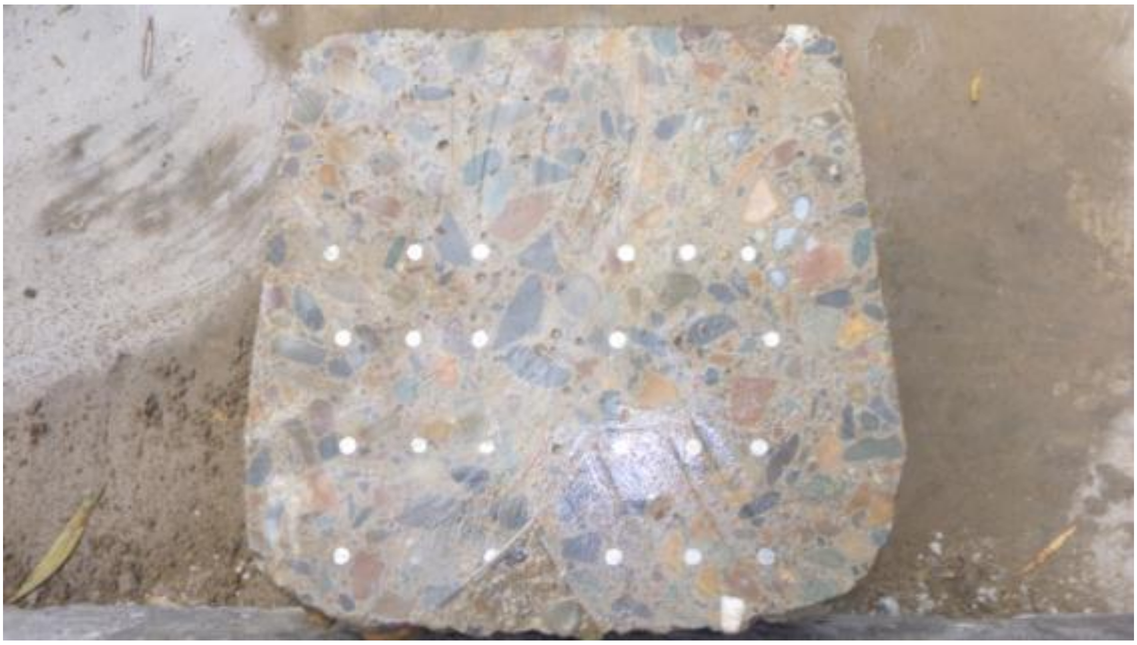


Figure 4. Freshly cut sleeper end ready for coring (SRA1)

Figure 5. Preparation of specimens for dynamic relaxation tests

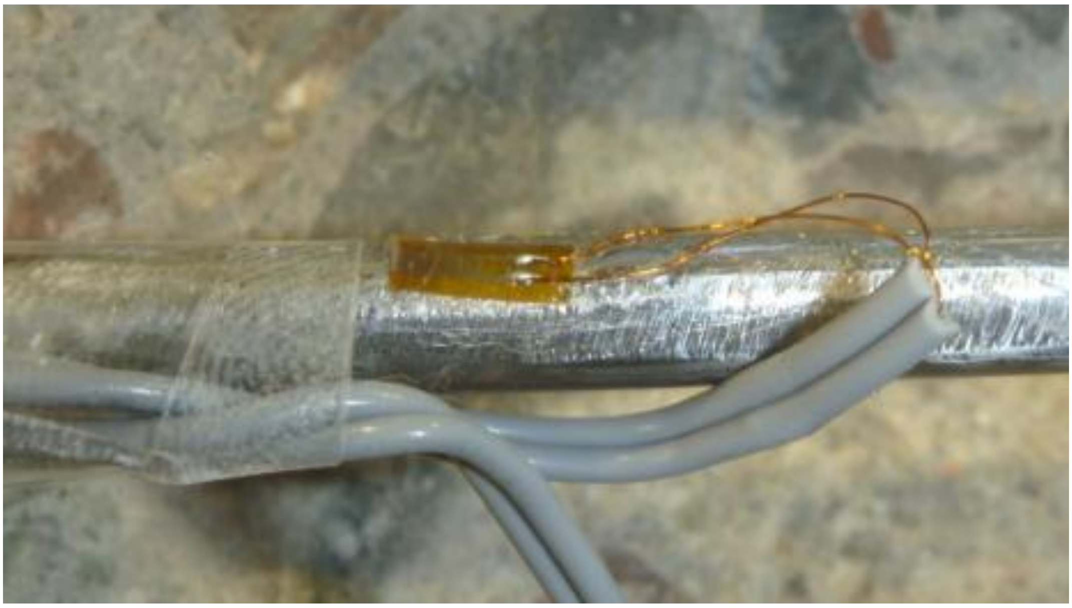
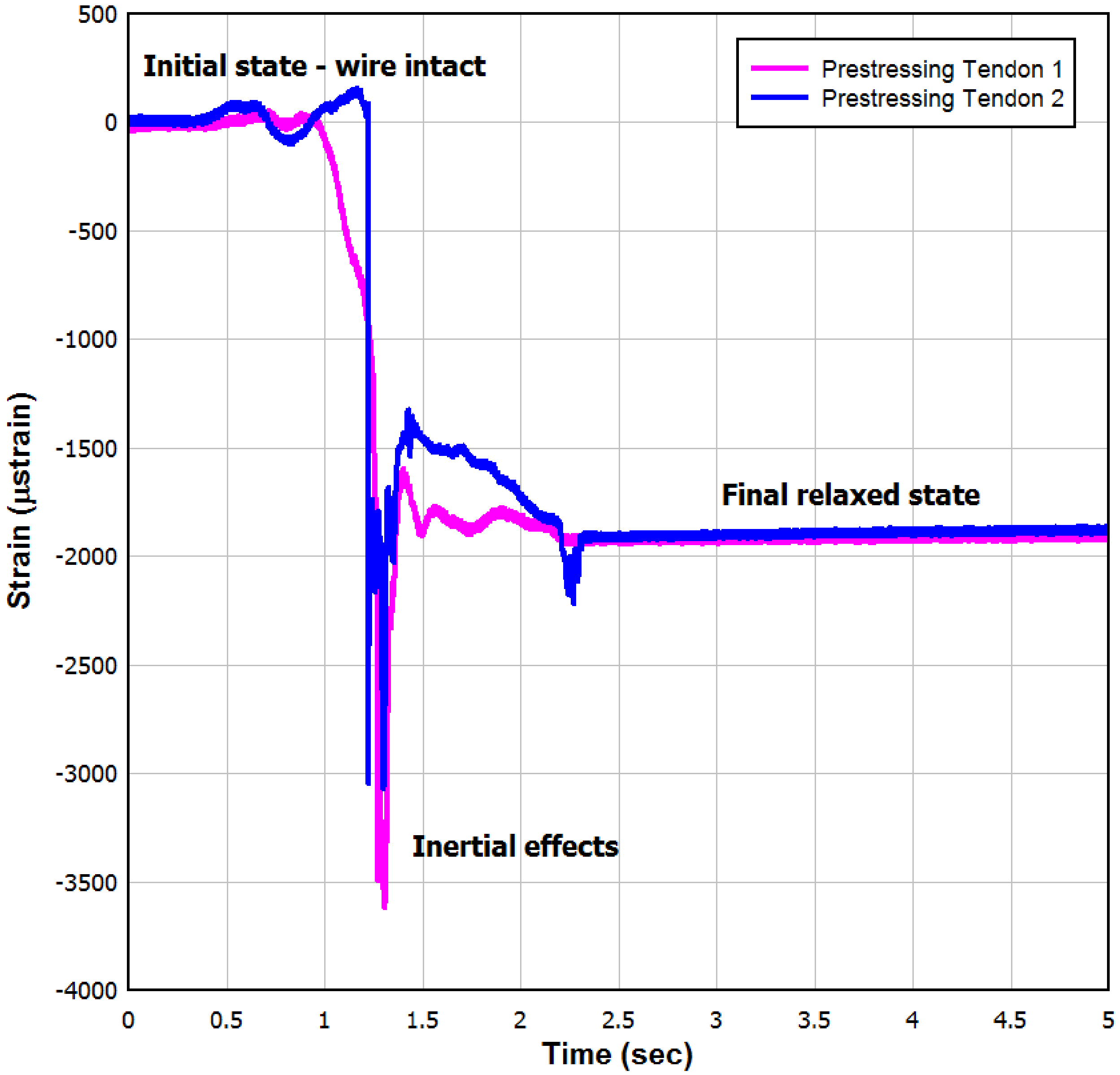


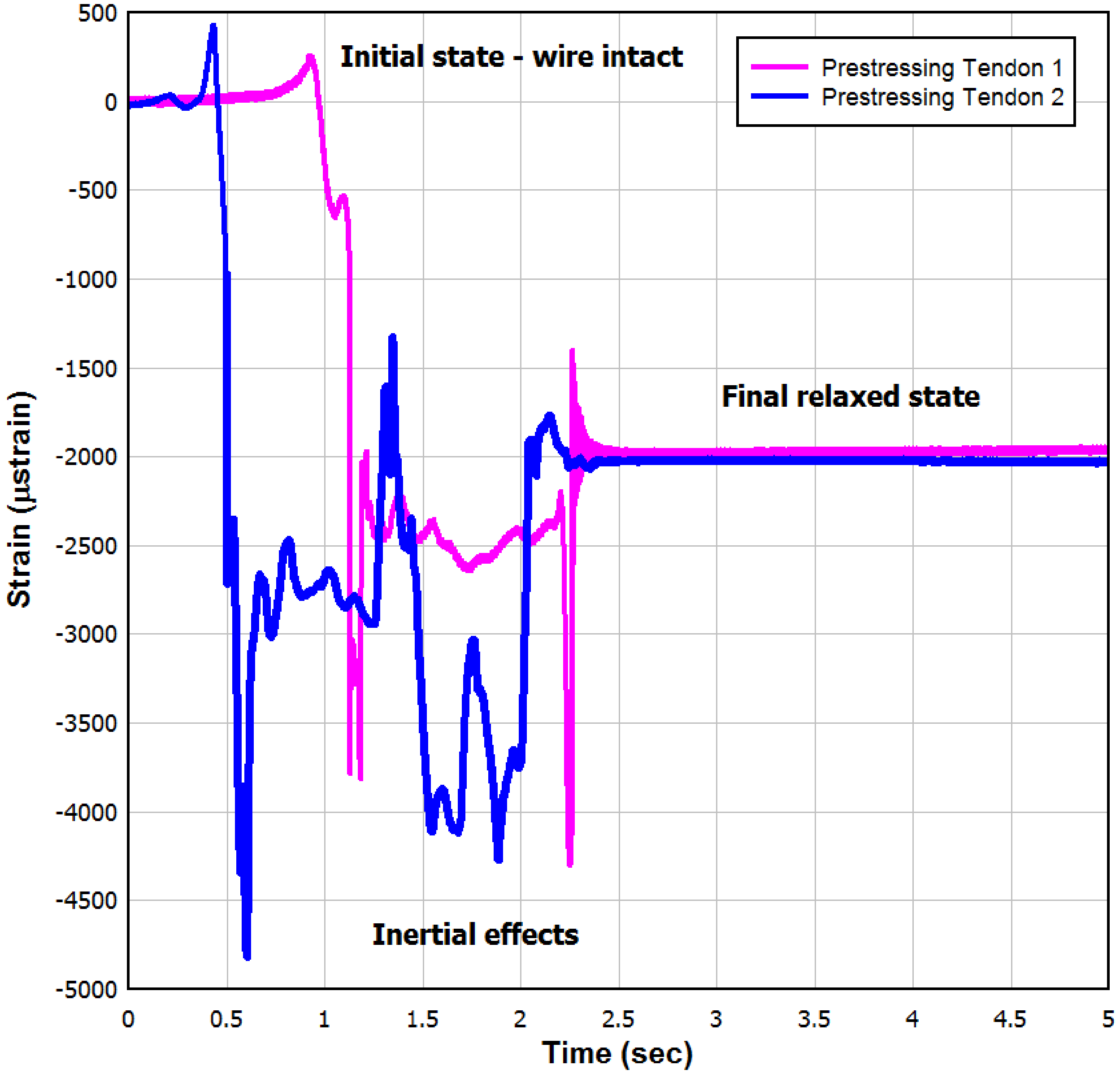
Figure 6. Two-millimetre strain gauges attached to prestressing wire

Figure 7. Cutting of prestressing wires



a) Coal-line Sleeper #1

Figure 8. Dynamic relaxation of prestressing force in prestress tendons for coal-line sleepers



b) Coal-line Sleeper #2

Figure 8. Dynamic relaxation of prestressing force in prestress tendons for coal-line sleepers

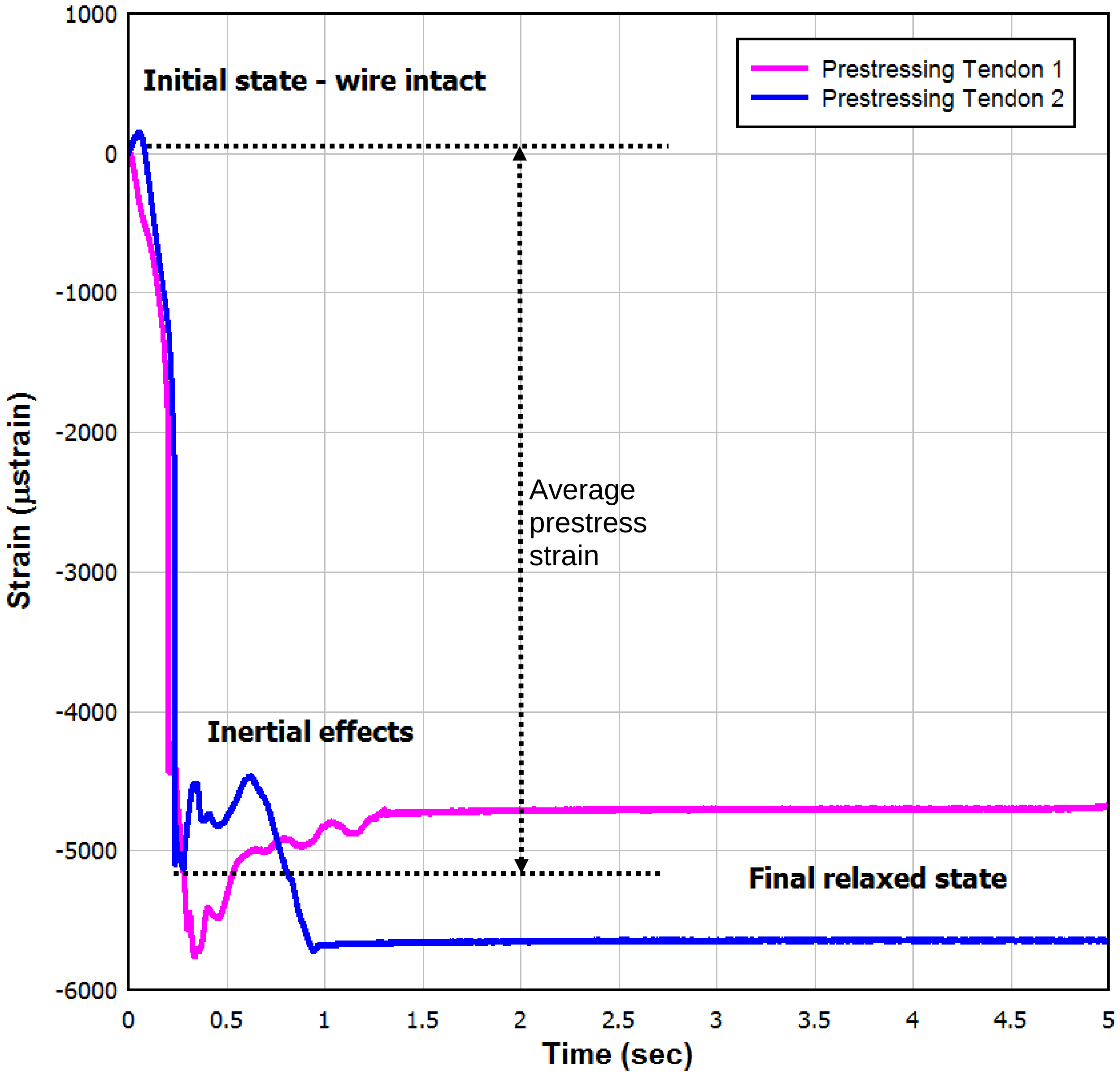


Figure 9. Dynamic relaxation of prestressing force in prestress tendons for ROCLA sleepers (validating test)

Figure 10. Sleeper end damage possibly resulting in considerable loss of prestress